LASER-TRIGGERED GAS SWITCH IMPROVEMENTS ON PBFA-II

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Summary and Introduction

PBFA-II is a thirty-six module ion accelerator built by Sandia National Laboratories for inertial confinement fusion feasibility studies [1]. In the water-filled, pulse-forming section of the accelerator, each module is fitted with a 5.0 MV, SF_6-filled gas switch located between an intermediate storage capacitor and the first pulse-forming line (Line 1). The intermediate storage capacitor is charged to 4.8-5.0 MV in approximately 950 ns by a Marx generator located in the oil section of the machine. The gas switch is required to close on command and transfer the stored capacitor energy to Line 1, a coaxial transmission line of 100 ns two-way electrical length. The switches are triggered by a single 3.0 J KrF laser located under the accelerator; a complex beam-splitting/distribution system is used to deliver simultaneous 20-40 mJ, 35 ns FWHM beamlets to the individual switches.

In order to properly drive the experimental load on PBFA-II, equal-amplitude pulses must be produced by each pulse-forming line with a module-to-module timing difference (spread) of less than 20 ns first-to-last. The gas switch - the last command-triggered point in the module - is the major determinant of total machine synchrony. To compensate for the additional (< 3 ns) jitter of three sets of self-breaking water switches downstream of the gas switches, timing spread of the 36 gas switches must be less than 15 ns first-to-last.

The PBFA-II gas switch set has been fired approximately 40 times since the first accelerator shot in 1985. In characterization tests over a limited parameter range (45-60 psia, 4.5-5.5 MV peak), attempts to obtain the low module-to-module spreads predicted from single-switch prototype experiments were unsuccessful. Typical first-to-last spreads were 40-150 ns, as a result of (a) high (4-10 ns) individual switch jitters and (b) occasional early lines due to prefires or switch housing flashovers.

In recent experiments on PBFA-II, gas switches have been modified and tested at different gas pressures and voltages. These modifications substantially reduced the switch runtime, jitter, and expected spread. Also, changes to the triggering KrF laser have been shown to significantly affect gas switch performance. The switch modifications will be incorporated into the machine as a retrofit planned for this summer. The laser optical set-up has also been changed as a result of these findings.

Approach

There are several competing theories on how best to distribute the voltage and E-fields across a multi-gap rimfire switch. One theory recommends low E-field in the trigger section, so that it determines neither self-break voltage nor prefire rate. This theory, which relies on a strong laser trigger to close the trigger section at a low percentage of self-break, was adopted in the original switch design [2,3]. A second theory advocates a higher trigger section E-field (equal to or greater than that in the rimfire gaps) so that the trigger section (a) is operating at a higher percent of self-break and (b) potentially dominates the prefire rate of the switch. Switches designed with this approach are not as strongly dependent on trigger level, and have been successfully operated on other Sandia accelerators [4].

The modification described herein was the result of a project to change the E-field distribution within the switch to maximize the trigger section E-fields and minimize the switch jitter. The JASON computer code [5] was used to determine the E-field distribution in the original switch. Figure 1(a) is a plot, generated from several JASON runs, of the E-field distribution along the original rimfire column and trigger section. The E-field values correspond to a voltage on the intermediate storage capacitor of 4.3 MV - the actual voltage across the switch terminals is 3.8 MV, due to the remote monitor location and capacitive voltage division with Line 1. This is the voltage at the time-of-arrival of the laser pulse in the trigger section of the switch, and results in a peak voltage of approximately 5.0 MV on the intermediate store at the time of switch closure.

The 131 kV/cm field in the center of the trigger section was the lowest in the switch, and the axial distribution in the trigger section was a deep trough with high (192 kV/cm) peaks at both electrodes. The U-shaped distribution was a result of (a) the electrodes' hemispherical shape and (b) large-radius holes in each electrode [6]. The distribution across the rimfire gaps was sloped, slanting from 230 kV/cm in the gap furthest from the trigger gap to 140 kV/cm in the gap nearest the trigger gap. This distribution was the result of additional metal added to the cathode end of the switch in an earlier shortening of the total switch gap.

A two-step modification was planned - a trigger section electrode change, followed by a total rimfire/trigger section change - to minimize risk and gain information on the relative effect of each change.

Trigger Section E-Field Redistribution

The objectives for the first modification were: (1) increase the field at the center of the trigger

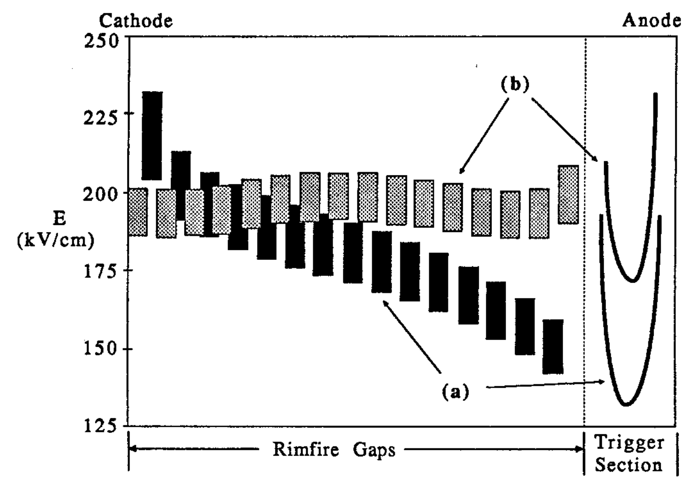

Figure 1. JASON-Derived Plots of the PBFA-II Gas Switch E-Field Distribution. Curve (a): Original Configuration. Curve (b): Final Modified Configuration.

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gap, (2) minimize the enhancement on the cathode electrode within the trigger gap, and (3) use the existing switch hardware. JASON was used to design electrodes that produced the desired profile across the trigger section (Figure 2). The modification involved removing the hole in the cathode electrode, reducing by one-third the diameter of the hole in the anode electrode, and reducing the radius of the anode hole from 0.64 cm to 0.15 cm. The result was a more-uniform-field profile, with (a) an 8 percent increase in field at the point of the laser-induced spark, i.e. on axis in the center of the gap, and (b) significant reduction of the cathode field enhancement.

Mallory 1000 trigger electrode inserts were fabricated and installed on four otherwise-unchanged switches. These switches were tested along with four unmodified switches at 50 psia and 4.8-5.0 MV peak. Results are tabulated in Figure 3. The modified switches consistently ran 7 ns faster than the original switches and exhibited an average 1-σ jitter of 5.5 ns versus an 8.3 ns average jitter for the original switches.

Total Switch E-Field Redistribution

The minor change to the trigger section E-field, coupled with the relatively high (30 percent decrease) effect on switch jitter implied the switch was still operating at a low percentage of self-break voltage. Consequently, a second modification was made, with the following objectives driving the final design:

1. Flatten the field distribution across the rimfire gaps.

2. Increase the ratio of trigger section field to peak rimfire gap field.

3. Raise the ratio of housing length to total gap to a level equal to or greater than existing, well-performing, switches.

4. Minimize changes to existing hardware.

These objectives were achieved with the design shown in Figure 4.

It was assumed, and later confirmed in tests on the DEMON accelerator [3], that the self-break voltage of the switch was determined by the field in the rimfire gaps furthest from the trigger section. This observation - that prefires initiate in the highest field gaps - implied that raising the field elsewhere in the switch would not significantly affect the self-break voltage. The ratio of the field where the laser-induced spark is generated (131 kV/cm, on axis in the center of the gap) to the peak field within the switch (230 kV/cm in the rimfire gap furthest from the trigger section) was 0.57. This ratio (though not a direct measure of percent of self-break at which the trigger section is operating [2]) was increased to 0.81, and the slope in the rimfire gap field distribution was eliminated, by (a) removing metal from the cathode end of the switch and (b) replacing the rimfire insulator nearest the trigger gap with an aluminum insert. The peak rimfire field of this interim design was reduced to 185 kV/cm.

The ratio of housing insulator length to total gas gap was then increased from 2.6 to 3.0, by adding another rimfire electrode, decreasing rimfire insulator length, and reducing the trigger gap from 5.1 to 4.4 cm. Similar gas switches operating at Sandia in the multi-megavolt regime have been shown to require a housing-to-gap ratio of this order to prevent housing flashover [4]. The resultant switch E-field distribution is shown in Figure 1(b); the E-field distribution in the acrylic housing and in the water outside the switch did not change. The modified switch has a 9 percent lower peak rimfire gap field (210

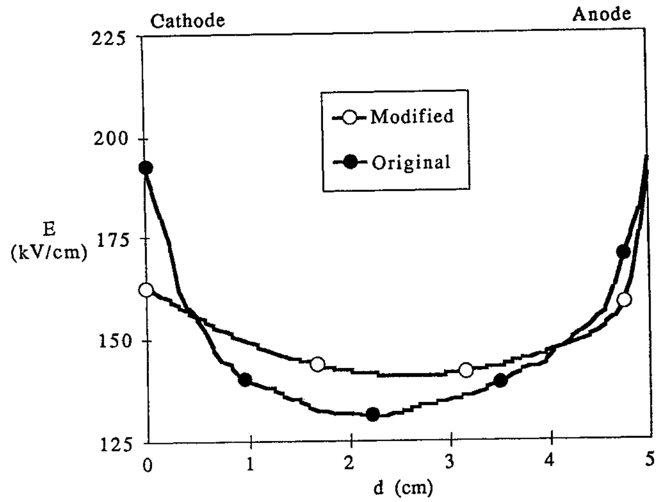

Figure 2. E-Field Plots of Trigger Sections with Original and Modified Electrode Inserts.

Switch No.	No. of Shots	Mean Runtime	Spread	Jitter
M1	6	82	10	3.5
M2	8	91	16	6.2
M3	7	86	9	3.5
M4	8	87	13	4.4
Total	29	87	19	5.5
U1	6	101	23	8.7
U2	3	85	4	2.0
U3	8	93	19	5.4
U4	8	96	30	9.4
U5	2	95	6	4.2
Total	27	94	35	8.3

Figure 3. Results of Trigger Section Modification Experiment. M = modified switch data, U = unmodified switch data. Units: ns.

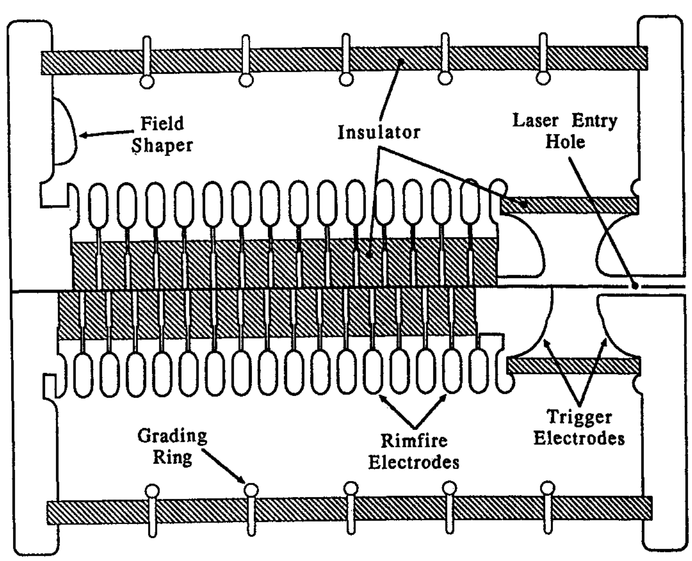

Figure 4. Comparison of Unmodified (Top) and Modified (Bottom) Gas Switch Designs.

kV/cm) than the original switch, and a 30 percent higher field in the trigger section at the point of the laser-induced spark (175 kV/cm). This E-field profile has been speculated to result in domination of the self-break voltage by the trigger section [2], though no confirming data is available.

Four switches were modified and fired in the PBFA-II accelerator, along with four unmodified switches. Over forty shots were taken, at gas pressures of 50 to 70 psia and peak voltages of 4.8-5.4 MV. For the initial test series, the machine timing was set for laser arrival at the switch with 4.3 MV on the intermediate storage capacitor. Corresponding peak voltage on the intermediate storage capacitor ranged from 4.8 to 5.0 MV, dependent on the runtime of the switch (dV/dt was approximately 6 kV/ns). The KrF laser delivered 25-35 mJ of energy to each switch in a beam with a spot size of 7.1 cm^2 incident on the 45 cm focal-length lens.

Series of shots were taken at 50, 60, and 70 psia and the results are tabulated in Figure 5. The runtime values in Figure 5 represent the time between arrival of the laser at the trigger gap and the zero-crossing of a V-dot monitor located in the middle of the intermediate storage capacitor. Actual closure time of the gas switch was not measured, but is at least 30 ns less than the values in Figure 5. Optical measurements are being carried out on the DEMON accelerator to determine the actual offset correction for the PBFA-II data [7].

At the 50 psia operating point, the modified switches consistently displayed a runtime 23 ns less than the original switches. Switch-to-switch variations in mean runtime and shot-to-shot jitter were significantly lower in the modified switches. At higher pressures, the differences between the two switch types were more pronounced. It is clear that the modified switch can operate at higher pressures with lower shot-to-shot jitter and spread.

KrF Laser Modification

A third experiment was motivated by a recent discovery that the laser beam in PBFA-II was significantly larger in diameter than the beam used on the DEMON accelerator - a PBFA-II testbed where prototype switches worked with lower runtime and jitter [3,8]. The beam spot size at the focusing lens was reduced from 7.1 cm^2 to 1.8 cm^2 by adjustment of the laser cavity optics, to determine the effect of the KrF beam energy density on switch performance. This change halved the beam convergence angle between the focusing lens and the focal point within the trigger gap, and can be viewed as effectively moving the focusing lens an additional 45 cm from the trigger gap and doubling its focal length. Measurements in a pressurized spark cell at 50 psia and 100 mJ incident energy revealed an approximate doubling of the visible sparklength and movement of the spark center toward the lens. Attempts to determine the effect on sparklength at 30 mJ were unsuccessful, as the visible spark could not be photographed [8].

Five shots were taken on each switch at 60 psia and the same 4.8-5.0 MV voltage as the previous series. The laser energy delivered remained 25-35 mJ, but the incident energy density was quadrupled as described above. The results are shown in Figure 5. No appreciable reduction in the modified switches' jitter was observed, though the runtime decreased 7 ns as a result of the 'hotter' trigger. The original switches, however, showed dramatic reductions in both runtime and average jitter, as runtime decreased by 19 ns and average jitter was reduced from 6.8 to 2.8 ns.

Discussion

The switch modifications were driven by criteria that assumed that a 'flat' rimfire E-field distribution and a relatively high trigger section mean E-field were needed to decrease the trigger section and total switch jitter. The resultant switch design performed well and is expected to have an acceptable prefire rate at the 5.0 MV operating point, since the peak field of 210 kV/cm is below the point at which other researchers have observed high self-break scatter [9]. There is uncertainty in predicting an operating point for the set of 36, since neither selfbreak voltage nor prefire rate was established at the pressures investigated in the experiment. The good performance at high pressure (70 psia), however, indicates the switches' low-jitter operating range may extend to 80 psia or above. Low-jitter performance at higher pressure appears achievable by increasing the effective focal length of the laser.

Additional statistical analyses of the data were carried out in attempts to remove the shot-to-shot variability from the data sets. The data were re-analyzed by subtracting the observed runtime for each switch from the average runtime observed on each shot. This procedure resulted in tabulations of mean offsets for each switch, and allowed runtime to be defined in the form:

$$\tau_n = K + a_n + \epsilon(\sigma_n)$$

where τ_n is the observed runtime of the nth switch, K is the mean runtime of all switches for a given shot, a_n is the inherent offset of the nth switch or machine

		M1	M2	M3	M4	Modified Switches		U1	U2	U3	U4	Unmodified Switches
50 psia 7.1 cm^2 beam (10 shots)	Runtime τ	65	58	65	67	$\Delta = 9$, $\bar{\tau} = 64$	Runtime τ	86	78	87	96	$\Delta = 18$, $\bar{\tau} = 87$
	Jitter σ	1.2	1.3	2.1	1.1	$\bar{\sigma} = 1.4$	Jitter σ	3.6	2.0	3.8	5.7	$\bar{\sigma} = 3.8$
60 psia 7.1 cm^2 beam (8 shots)	Runtime τ	70	63	69	72	$\Delta = 9$, $\bar{\tau} = 69$	Runtime τ	103	84	96	114	$\Delta = 30$, $\bar{\tau} = 99$
	Jitter σ	1.6	1.8	2.2	2.3	$\bar{\sigma} = 2.0$	Jitter σ	7.0	3.3	6.2	10.8	$\bar{\sigma} = 6.8$
70 psia 7.1 cm^2 beam (7 shots)	Runtime τ	71	65	71	74	$\Delta = 9$, $\bar{\tau} = 70$	Runtime τ	104	86	97	111	$\Delta = 25$, $\bar{\tau} = 100$
	Jitter σ	3.1	3.6	3.2	2.4	$\bar{\sigma} = 3.1$	Jitter σ	10.2	2.8	5.4	6.4	$\bar{\sigma} = 6.2$
60 psia 1.8 cm^2 beam (5 shots)	Runtime τ	63	57	63	65	$\Delta = 8$, $\bar{\tau} = 62$	Runtime τ	80	72	80	87	$\Delta = 15$, $\bar{\tau} = 80$
	Jitter σ	2.1	2.1	2.2	1.5	$\bar{\sigma} = 2.0$	Jitter σ	2.6	1.9	2.9	3.7	$\bar{\sigma} = 2.8$

Figure 5. Results of the Total E-Field Modification Experiment. Units: ns.

module, and $a(\sigma_n)$ is the random variation of the switch with mean a and standard deviation σ. K is a function of charge voltage on the Marx generators or intermediate storage capacitors, the gas pressure and purity, laser quality and energy level, and other variables common to all switches on a given shot. a_n is a function of laser energy delivered to a given module, individual intermediate store capacitance, individual switch electrode columns, module optics, etc.

Spread for a shot is defined as the range of τ_n with n = 36. K, by being common to each switch runtime, will not contribute to the shot spread. The contribution of the individual a's will be a constant for every shot, and can be reduced by individual adjustment or 'tuning' of the laser pathlength to each switch.

The modified switch data, at 60 psia with a 7.1 cm^2 laser beam, takes the following form when analyzed in this manner:

$$\tau_{M1} = 69 + 1.5 + \epsilon(0.5) \text{ ns}$$
$$\tau_{M2} = 69 - 5.3 + \epsilon(1.0) \text{ ns}$$
$$\tau_{M3} = 69 + 0.2 + \epsilon(1.0) \text{ ns}$$
$$\tau_{M4} = 69 + 3.6 + \epsilon(1.5) \text{ ns}$$

This analysis implies spread on any given shot of these four switches of 7-11 ns. Further analysis of this data set predicts a 36-module spread of 20 ns, assuming no adjustment of laser pathlengths. Predicted 36-module spread decreases to 5 ns, if the switch-to-switch variability (a) is adjusted to zero. Similar projections of 6 ns spread at 50 psia and 8 ns spread at 70 psia have been made, when offsets are assumed to be adjusted to zero.

Analysis of the raw data reveals a strong dependence of switch jitter on the switch runtime. Figure 6 is a plot of switch jitter versus runtime for each of the switches at each operating point. From the graph, it can be seen that reducing the switch runtime below 80 ns is necessary to deliver sub-3 ns jitter. The modification to the switch E-field distribution and profile resulted in sub-80 ns runtime in all experimental series; as a result, improving the laser trigger did not significantly improve switch jitter. Substantial runtime reduction of the unmodified switches, however, was achieved by increasing the effective laser focal length.

Conclusion

Laser-triggered gas switches on PBFA-II have been shown to operate with low (sub-3 ns) shot-to-shot jitter when the runtime is less than 80 ns. Two methods of reducing the switch runtime have been demonstrated: (1) flattening the E-field distribution across the rimfire stack and increasing the trigger section E-field and (2) increasing the effective focal length of the incoming laser beam. Modification of the switch E-field distribution resulted in low runtime and shot-to-shot jitter over the range of 50-70 psia at nominal peak voltages of 4.8-5.0 MV. Four modified switches were tested, and consistently operated with sub-3 ns jitter. Analyses that remove common shot-to-shot differences reveal actual switch jitters less than 2 ns.

Similar reductions in runtime were accomplished in a separate experiment by reducing the spotsize of the incoming laser beam at the focusing lens. Switch runtime and jitter were substantially reduced in the original PBFA-II gas switches; switches with the modified E-field distribution showed modest reductions in runtime and immeasurable improvement in jitter.

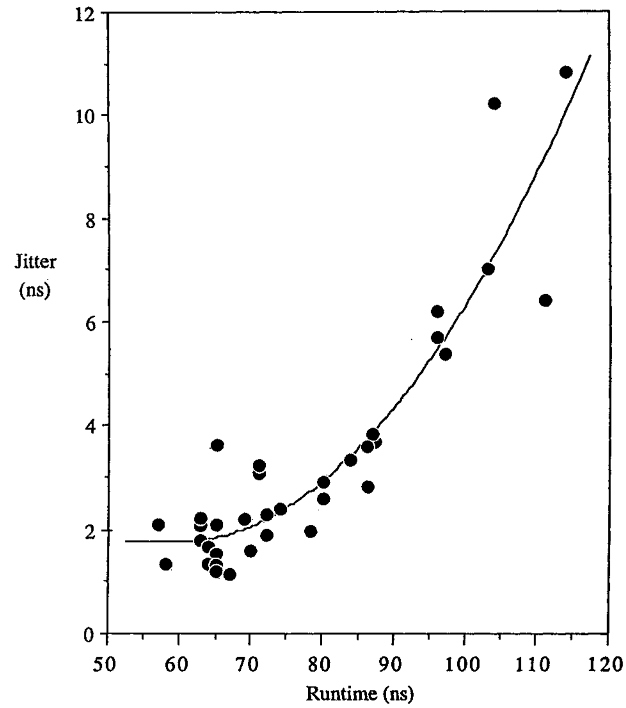

Figure 6. Plot of Switch Jitter versus Runtime for Total E-Field Modification Experiment

Plans are underway to retrofit the PBFA-II accelerator with 36 modified switches this summer. Total 36-module spread of less than 15 ns is predicted by extrapolation of these four-module results.

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